

## THE 1996 CONTROLLED FLOOD IN GRAND CANYON: FLOW, SEDIMENT TRANSPORT, AND GEOMORPHIC CHANGE

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**Abstract.** The 1996 controlled flood released from Glen Canyon Dam into the Colorado River was a small magnitude, short duration event compared to pre-dam floods. The controlled flood was of lesser magnitude than a 1.25-yr recurrence, and only 10% of the pre-dam spring snowmelt floods during the period 1922–1962 were of lower magnitude. The flood occurred unusually early: 36–38 d prior to any previous annual flood since 1922. The stage difference between the flood's peak and the recessional baseflow was smaller than in those pre-dam years of similar magnitude or annual volume.

However, the controlled flood was large from the perspective of the post-dam flood regime. The flood had a recurrence of 5.1 yr for the period between 1963 and 1999 and a similar magnitude flood had not occurred in 10 yr. The sediment flux of the flood was small in relation to pre-dam floods, and the suspended sand concentration was within the historical variance for flows of similar magnitude.

This flood reworked fine-grained deposits that are primarily composed of sand, but the flood caused much less reworking of coarser grained deposits. Scour primarily occurred in the offshore parts of eddies, in many eddy return-current channels, and in some parts of the main channel. Return-current channels constitute important nursery habitats for the native fishery when baseflows are low, because these channels become areas of stagnant and warmer water. The number and area of these backwaters increased greatly after the flood. Fluvial marshes were extensively scoured because these habitats occur in the low elevation centers of eddies where velocities during the flood were large. Riparian shrubs that were inundated along the banks were not scoured, however, because these shrubs occur where flood velocities were very low and where deposition of suspended sediment occurred. Some physical changes persisted for several years, but other changes, such as the area of newly formed backwaters decreased quickly. Thus, the lasting effect of this flood varied among different small-scale fluvial environments.

**Key words:** Colorado River; ecosystem; flood; geomorphology; Glen Canyon Dam; hydrology; management.

### INTRODUCTION

In many regulated rivers, scientists seek to understand the relationship between the magnitude and duration of floods and the resulting ecological disturbance. Controlled floods, such as the one that was released from Glen Canyon Dam in spring 1996, are being introduced into some regulated rivers, but there is a limited amount of water that can be allocated to these flow events. Thus, managers want to know how to efficiently provide a flood disturbance to a regulated river while using a minimum volume of water.

Large floods often cause geomorphic changes in the channel and adjacent alluvial valley (Mayer and Nash 1987, Baker et al. 1988, Bevin and Carling 1989), and

these changes have the potential to alter the structure and function of associated aquatic and riparian ecosystems (Resh et al. 1988, Junk et al. 1989, Stanford et al. 1996, Poff et al. 1997). Floods may be characterized in terms of hydrology, hydraulics, sediment transport, and the magnitude and extent of aggradation and degradation. These attributes cause disturbance by hydraulic stress and erosion and deposition of substrates that constitute habitat of flora and fauna.

The purpose of this paper is to describe the hydrologic, hydraulic, and sediment transport characteristics, as well as the resulting landform changes, caused by the 1996 controlled flood on the Colorado River downstream from Glen Canyon Dam (Webb et al. 1999b). We compare this flow event with other floods of the Colorado River that occurred before and after completion of the dam, and we ask whether this flow was a

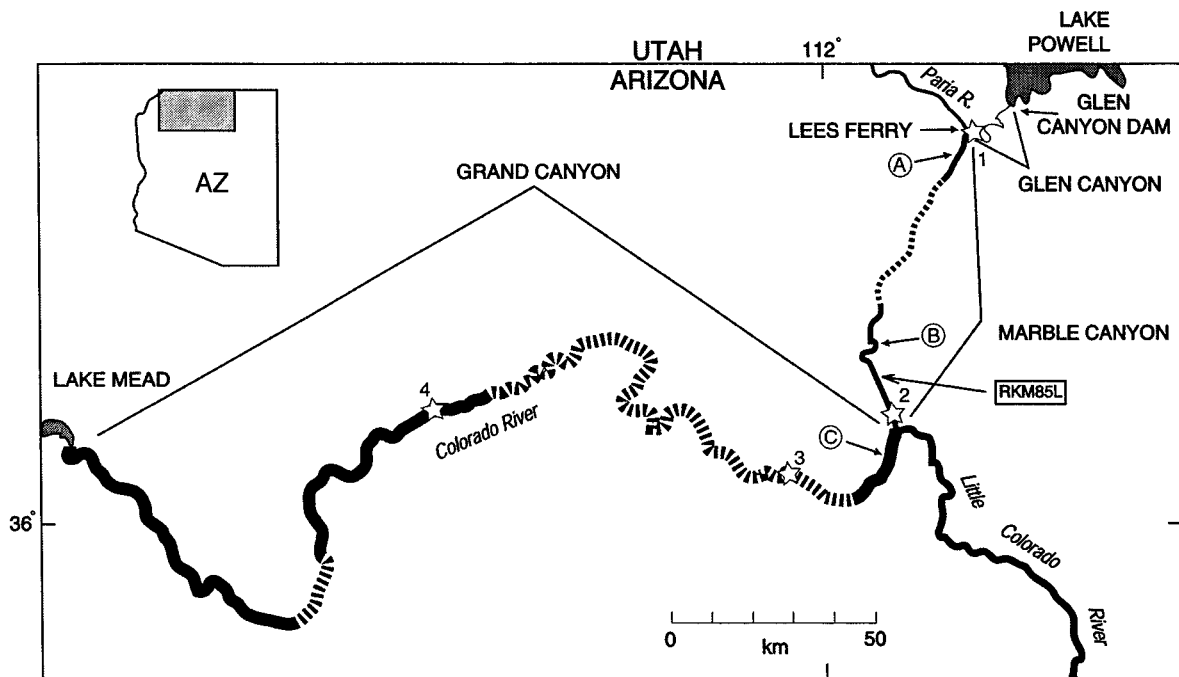


FIG. 1. The Grand Canyon region. Width of the trace of the Colorado River, Paria River, and Little Colorado River is proportional to the post-dam fine sediment load, as estimated by Topping et al. (2000). Dashed river segments are those with a narrow channel in relation to other reaches. Stars are locations of U.S. Geological Survey gaging stations. 1, Colorado River at Lees Ferry, Arizona; 2, Colorado River in Lower Marble Canyon, near Desert View, Arizona; 3, Colorado River near Grand Canyon, Arizona; and 4, Colorado River at National Canyon, near Supai, Arizona. Letters A, B, and C are locations of detailed maps shown in Fig. 2.

hydrologically and geomorphically significant disturbance. This review supplements the findings of Webb et al. (1999b) and includes additional data on changes in critical aquatic habitats. This review therefore provides background with which the reader can evaluate companion papers that describe ecological responses to this flow event.

#### EVALUATING FLOOD IMPACTS

Analysis of the landform changes caused by the 1996 controlled flood requires consideration of the characteristics of the channel and adjacent valley immediately prior to the flood, longitudinal characteristics of channel gradient and valley width, and the sequence and magnitude of previous floods. The impact of a specific flood must be evaluated within the context of that specific river/flood/floodplain environment, because the resistance to erosion of the banks and alluvial valley is determined by substrate, soil development, and vegetation (Nanson and Croke 1992), longitudinal variation in stresses exerted by the flood (Magilligan 1992), and the temporal ordering of previous floods (Yu and Wolman 1987, Kochel 1988). Some large magnitude floods have the potential to rearrange a large proportion of the alluvial valley, but similar magnitude floods in other river systems cause few changes (Magilligan et

al. 1998) because the same magnitude flood will cause less change if it occurs soon after a previous large flood.

#### THE PHYSICAL TEMPLATE FOR THE AQUATIC AND RIPARIAN ECOSYSTEM

##### *The large-scale template*

The physical template of the Colorado River ecosystem downstream from Glen Canyon Dam has two spatial scales, and analysis of the effects of the 1996 controlled flood must be made within the context of both scales. The large-scale control on channel and floodplain processes arises from the geologic history of the southern Colorado Plateau that has determined the (1) location of the river's course, (2) relief, width, and location of canyons, (3) location of major tributaries and the characteristics of flow and sediment transport of those tributaries, (4) seasonal and spatial patterns of precipitation, and (5) elevation of geologic formations whose failure generates debris flows during intense rains. The 400 km between the dam and Lake Mead reservoir is divided into Glen, Marble, and Grand Canyons (Fig. 1), and the primary large-scale controls on channel and floodplain form are the lithology of the bedrock that occurs at river level and the size and number of debris fans that partially block the river's course (Howard and Dolan 1981, Schmidt and Graf 1990, Mel-

is 1997). The alluvial valley is wider and has a lower gradient where erodible rocks occur at river level, and talus, bouldery debris fans, or sandy alluvium are the channel's banks. Stresses exerted by a flood are typically less in these reaches. In contrast, the banks are bedrock in some reaches bounded by metamorphic rocks or limestone. The gradient is steepest and flood induced stresses are greatest in these narrow reaches. The number and size of eddies that exist during floods are greatest where debris fans are large in size and frequent in number.

Most of the river's sediment load consists of particles <0.5 mm in size (Smith et al. 1960), and the distribution of large tributaries determines the quantity of fine sediment available for transport during floods. The annual load delivered to Grand Canyon from the upper Colorado River basin, which was  $\sim 57 (\pm 3) \times 10^6$  metric tons/yr between 1949 and 1962 (Topping et al. 2000), is now deposited in Lake Powell reservoir. The flux of fine sediment is now largely determined by the distribution of sediment available for entrainment that is stored on the channel bed, in bars, or in banks, and this sediment is either relict from pre-dam conditions or is supplied from unregulated tributaries. The largest sources of sediment supply to the post-dam Colorado River are the Paria River and the Little Colorado River (LCR). Between 1949 and 1970,  $3.0 (\pm 0.6) \times 10^6$  metric tons/yr of sediment entered the Colorado River from the Paria River, of which  $\sim 50\%$  was sand, and  $8.6 (\pm 1.7) \times 10^6$  metric tons/yr of sediment entered from the Little Colorado River, of which  $\sim 30\%$  to  $40\%$  was sand (Topping et al. 2000).

Thus, the Colorado River downstream from the dam can be divided into three reaches in terms of the magnitude of the fine sediment flux (Fig. 1). The 25-km reach upstream from Lees Ferry has little tributary contribution. The Paria River is the primary supplier of fine sediment to the 100 km downstream from Lees Ferry. The Little Colorado River delivers a large load of fine sediment, and its confluence occurs 125 km downstream from the dam.

The greatly reduced sediment transport has increased water clarity, thereby converting a historically heterotrophic, allochthonous system to an autotrophic system dependent on autochthonous production (Brock et al. 1999, Marzolf et al. 1999). There is high photosynthetic productivity in Glen Canyon, where the trophic structure is supported by the green alga, *Cladophora glomerata*, and a large assemblage of epiphytic diatoms (Blinn et al. 1995, Stevens et al. 1997). This tailwater reach is ideal for the blue-ribbon nonnative trout fishery that was introduced there. Productivity decreases greatly downstream, but water clarity is still high enough to affect behavior of the endangered humpback chub (*Gila cypha*) because of risk of predation by the abundant nonnative fishery (Valdez and Ryel 1997).

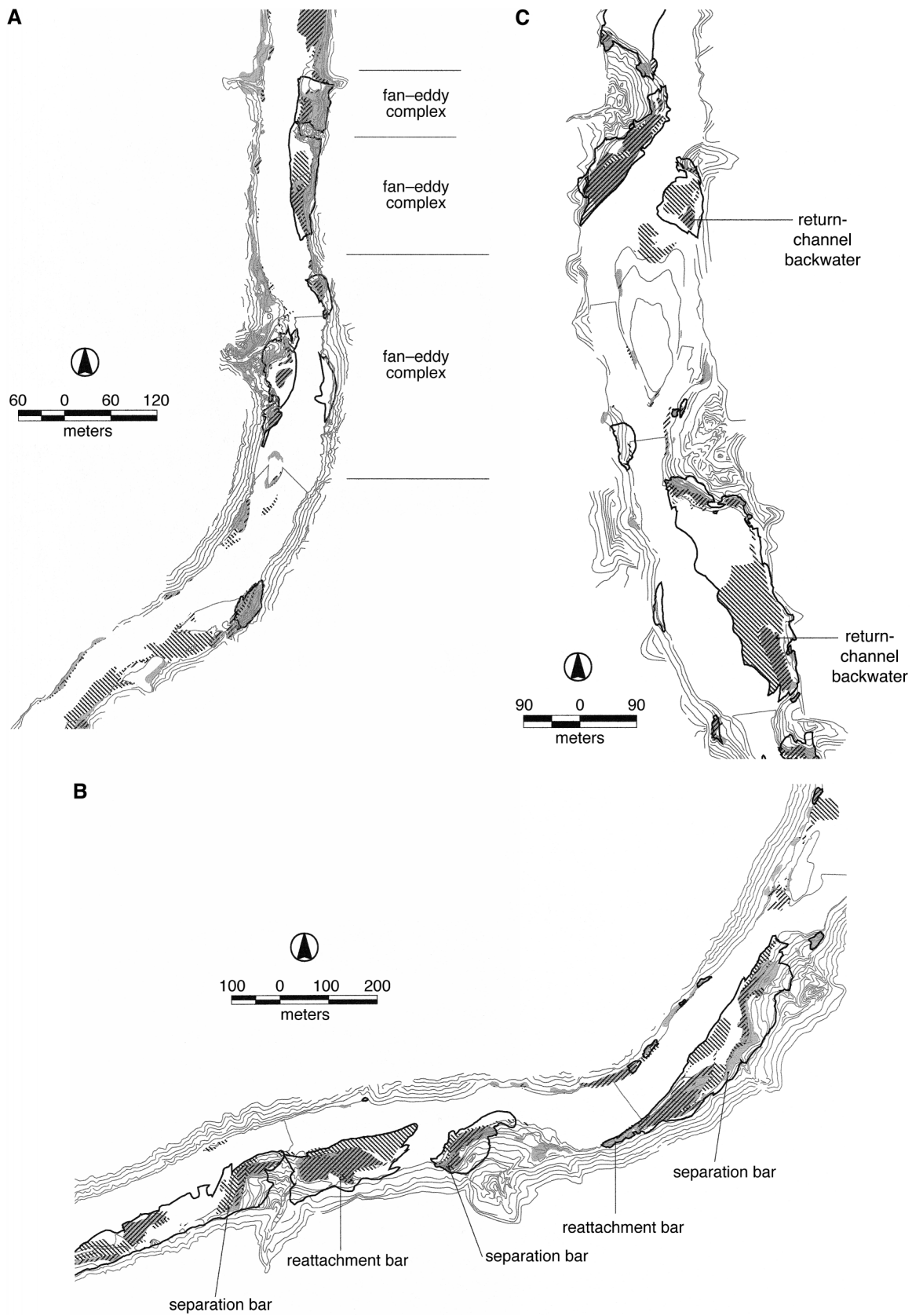
### *The small-scale template*

At a smaller scale, the distribution of habitats and the locations of erosion and deposition during floods are determined by the hydraulic patterns created by the debris fans (Fig. 2). White-water rapids all occur where debris fans, composed of boulders too large to be transported by the river, partly block the flow. Blockage creates a reach of low-velocity, ponded flow that may extend several kilometers upstream from each fan (Kieffer 1985). Large eddies typically occur immediately downstream from rapids, and gravel bars exist further downstream. Schmidt and Rubin (1995) adopted the term fan-eddy complex for the length of the main-stem river between the ponded upstream flow and the downstream gravel bar, because the hydraulics of the intervening reach are determined by a specific debris fan.

The channel bed of the ponded flow is typically composed of sand. The banks are also composed of sand and occur as a series of distinct benches, each with a natural levee. The sand in these banks has been transported as suspended load, and the landforms are called channel-margin deposits (Schmidt and Rubin 1995). Most of these deposits have been densely colonized by native and nonnative phreatophytes since completion of the dam (Turner and Karpiscak 1980, Johnson 1991, Stevens et al. 1995).

Recirculating eddies downstream from rapids are utilized by the native and nonnative flora and fauna. These eddies are large and numerous. Schmidt et al. (1999b) found that the surface area of the largest eddies in 31 km of Grand Canyon is nearly 40 000 m<sup>2</sup> at some discharges and that the average size of eddies is between 7250 m<sup>2</sup> and 10 000 m<sup>2</sup>. Circulation in these eddies is typically one-celled, with strong upstream velocity along the bank. Pockets of low, or zero, velocity exist in the lee of each debris fan and near the zone of flow reattachment, which is the downstream end of the eddy. High rates of sedimentation exist in these eddies when the main flow carries a large sediment load, because the transport capacity of eddies is much less than the main flow. Eddies change in size as discharge changes, because the velocity of the rapid and the geometry of the channel constriction and expansion change (Schmidt 1990).

The bed topography of an eddy includes a platform of shallow sand beneath the primary eddy (called a reattachment bar), a deep channel between the platform and the adjacent bank (called the primary eddy return-current channel), and a platform of sand mantling the downstream part of the debris fan (called a separation bar). Water in the deep channel between the separation and reattachment bar becomes a stagnant embayment at low discharges when the bar platform is emergent and blocks circulation from the main flow. This and other shoreline embayments are referred to as backwaters. Embayments formed in return-current channels





over the range of discharges common to the post-dam river have been identified as the most significant backwater environments for detailed study and management (U.S. Bureau of Reclamation 1995). These areas are used extensively as nurseries by young native and non-native fishes and as rearing and holding areas by small fishes.

By 1995, most of the large backwaters had aggraded with silt and were overgrown by marsh and bar vegetation (U.S. Bureau of Reclamation 1995), thereby shifting this geomorphic setting from a fish nursery habitat to a fluvial marsh.

This deposition pattern and shift in habitat has typically occurred within five years following each post-dam flood (Stevens et al. 1995). This shift impacts nutrient distribution and water-holding capacity in the vadose zone. Sediments rich in N, P, and organic carbon are largely restricted to return-current channels. Clays and allochthonous organic matter improve the water-holding capacity of the sediments, increase sediment cohesiveness, and are likewise restricted to return-current channels. During high flows, the river inundates the bar surface, reactivates flow in the return-current channel, and may scour the return channel of silt, clay, and organic debris. One goal of the test flood was to rejuvenate these habitats.

Dam-induced changes in hydrology and sediment supply have altered the texture of other bar and bank substrates as well, which in turn has affected riparian plant succession and productivity (Stevens 1989, Stevens et al. 1995). Typically, bars reworked by post-dam floods are coarser than higher elevation pre-dam deposits. Deposition of silt, clay, and organic materials only occurs at the time of tributary floods in low velocity environments such as backwaters, and silt and clay are not deposited across the entire reattachment bar surface (Parnell et al. 1999).

Downstream from the eddies, bars composed of gravel and cobbles occur in the main channel. These bars are composed of debris entrained from the debris fan located immediately upstream (Webb et al. 1997, Pizuto et al. 1999). Elsewhere, gravel bars occur in Glen Canyon and the wider reaches of Grand Canyon (Schmidt et al. 1999b). Gravel bars in Glen Canyon are known spawning sites for rainbow trout, but the ecological role of gravel and cobble bars elsewhere has not been studied.

## CHARACTERISTICS OF THE CONTROLLED FLOOD

### Hydrology

The controlled flood was a small event in the context of pre-dam flows, because the flood was of short duration and small magnitude. The controlled flood consisted of a rapid rise from 227 m<sup>3</sup>/s to a steady high discharge of 1274 m<sup>3</sup>/s that lasted for 7 d. The flow then receded to 227 m<sup>3</sup>/s, and this low discharge lasted for 3 d. Thereafter, normal flows resumed (Schmidt et al. 1999a; Patten et al. 2001 in this issue). The magnitude of the controlled flood was less than the pre-dam 1.25-yr recurrence flood of 1465 m<sup>3</sup>/s, calculated using a log-Pearson Type III distribution for the period 1922 to 1962. Only four (10%) of the water years during the pre-dam period of stream gaging had peak discharges less than the magnitude of the controlled flood: 1931, 1934, 1954, and 1955 (Fig. 3). The test flood was larger than floods in 9 of the 40 yr (23%) of pre-dam data (1 in 4.4 yr), in terms of the total volume of water of the flood as measured by the product of mean daily discharge and number of days exceeding 1270 m<sup>3</sup>/s (Fig. 4).

The duration of the controlled flood was short in comparison to those pre-dam years when similar magnitude floods occurred, and the magnitude and duration were low in comparison to pre-dam years when the same total annual amount of streamflow passed through Grand Canyon. The difference in magnitude between the controlled flood and baseflows during the rest of the year was less in 1996 than in those pre-dam years of similar magnitude or annual volume. For example, peak flows in 1940 and 1960 were approximately the same as in 1996, but the baseflows to which the Colorado River receded in those pre-dam years were more than 300 m<sup>3</sup>/s less than the typical baseflows following the test flood (Fig. 5).

The test flood occurred 36 to 38 d earlier in the year than any previously measured high flow of this magnitude. The median and mean dates when mean daily discharge first exceeded 1270 m<sup>3</sup>/s were 8 May and 10 May, respectively, for the period between 1922 and 1962. The earliest date in any year during this period when flows exceeded 1270 m<sup>3</sup>/s was 8 April 1942.

In contrast to the pre-dam hydrology of this system, the magnitude of the controlled flood was large in relation to flows that occurred after completion of Glen Canyon Dam. The test flood was one of seven high

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FIG. 2. Patterns of erosion and deposition along the Colorado River caused by the 1996 controlled flood (A) near Lees Ferry, (B) near Point Hansborough, and (C) downstream from the Little Colorado River. Locations of these areas are shown on Fig. 1. Dark lines surround the maximum eddy bar area, as determined by historical aerial photograph analysis by Schmidt et al. (1999b) and H. Sondossi and J. C. Schmidt (*personal communication*). Gray shaded areas are where deposits created by the 1996 controlled flood occurred. Hatched-line areas sloping from upper right to lower left are where deposition exceeded 25 cm, and hatched-line areas sloping from upper left to lower right are where erosion exceeded 25 cm.

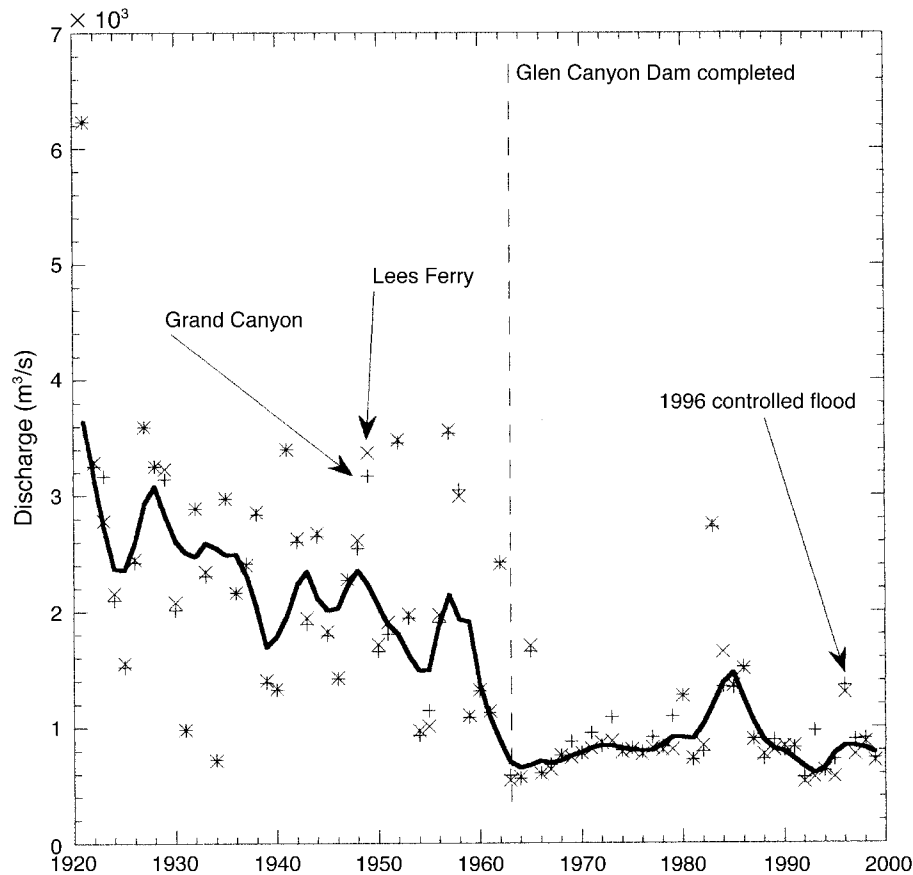


FIG. 3. Time series of annual peak discharges at the Lees Ferry and Grand Canyon gaging stations. The thin solid line is the 10-yr weighted average peak discharge.

flow events in the 36-yr history of regulated flows in this system, a 5.1-yr recurrence, and the largest flow in a decade (Fig. 3). The largest instantaneous peak discharge released from Glen Canyon Dam occurred in June 1983 and was 2724 m<sup>3</sup>/s. Flows comparable in magnitude to the controlled flood, but of longer duration, occurred in 1965, 1980, and annually between 1984 and 1986.

#### Hydraulics

Flow velocity and unit stream power are related to the forces exerted on bed and bank sediments and on benthic and riparian vegetation. Thus, these are appropriate attributes of the flood with which to measure potential disturbance to the riparian and aquatic communities. Measurements during the controlled flood demonstrate the large longitudinal and cross-sectional variation in flow speed that is characteristic of confined rivers. During flood, these rivers typically have very fast main-stem velocity yet also have areas where velocity is zero or is upstream. This diverse range of hydraulic conditions creates areas where bed or bank erosion dominates, areas where sediment deposition

occurs, and areas that provide refugia for aquatic organisms.

The highest velocity occurred in rapids. Webb et al. (1997) measured the mean surface speed of the left side of Lava Falls Rapid to be 6.6 m/s. Pizzuto et al. (1999) calculated the average velocity along the left bank at the same rapid to be between 0.9 and 3.9 m/s. These velocities are consistent with estimates made by Kieffer (1985) for the velocity of Crystal Rapid at 2602 m<sup>3</sup>/s in June 1983. She estimated average speeds as large as 8.7 m/s in the fastest part of the rapid.

In contrast, velocity in the zones of flow separation and reattachment that determine the upstream and downstream ends of eddies was zero. However, the locations of these low velocity zones changed. Velocity elsewhere in eddies varied greatly, and was typically highest in the upstream return current. We measured the maximum upstream velocity in one inundated return-current channel in lower Marble Canyon to be 0.9 m/s.

Reach-average velocity was measured by recording the times at which a red fluorescent dye moved downstream past various measurement stations (Graf 1995).

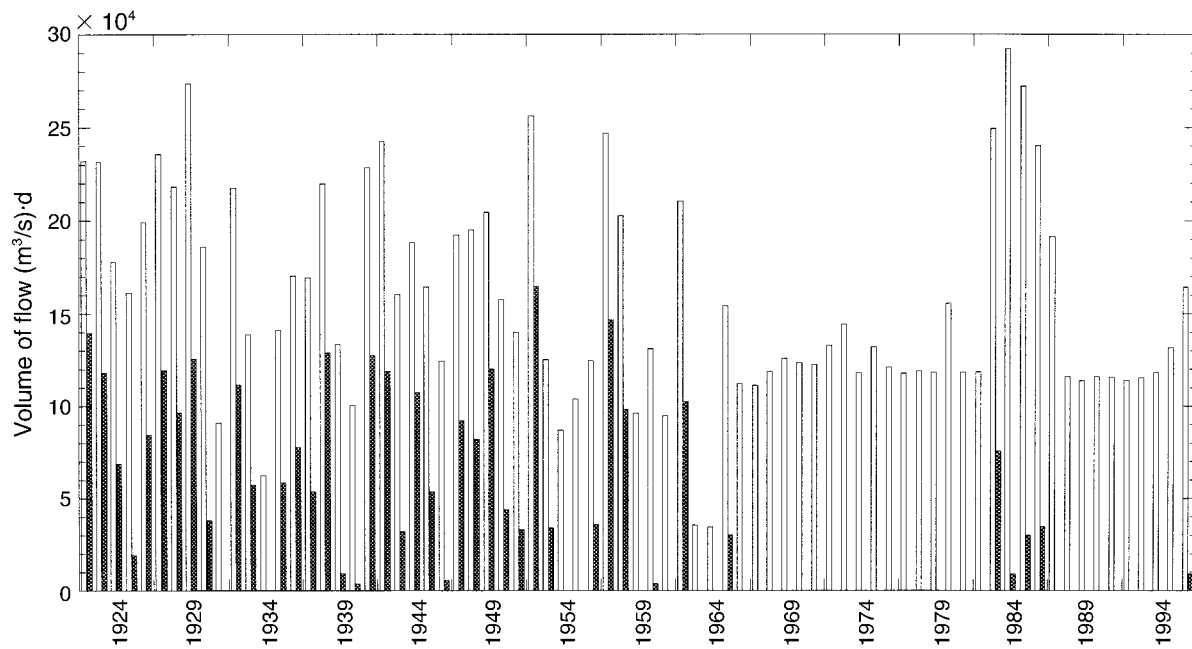


FIG. 4. Time series of the annual volume of flow and the annual volume of high flows. The annual volume of flow is measured in cubic meter per second days, in open bars, and the annual volume of high flows is measured in cubic meters per second days when mean daily discharge exceeded  $1270 \text{ m}^3/\text{s}$ , in dark bars.

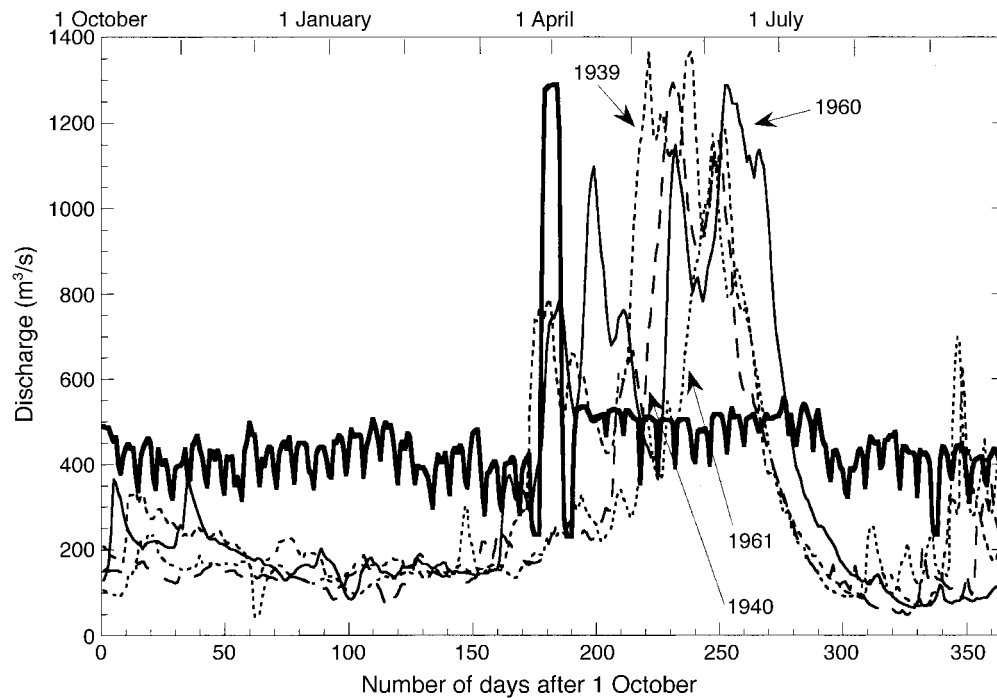


FIG. 5. Annual hydrographs for the 1996 controlled flood (thick solid line) and for four pre-dam years in which the magnitude of the annual flood was similar to that in 1996.

The average speed of the flood for the entire river length was 1.8 m/s, varying from  $\sim 1.5$  to 2.1 m/s in different subreaches that were tens of kilometers in length (Konieczki et al. 1997). However, velocities varied greatly over shorter distances.

Although Magilligan (1992) proposed that geomorphically effective floods typically have unit stream power values exceeding  $350 \text{ W/m}^2$ , the great variation in flow conditions in Grand Canyon makes such arbitrary thresholds of limited value. There were areas where energy expenditure was far greater than the threshold suggested by Magilligan (1992) and other places where the expenditure was far less. Smith (1999) calculated the skin friction shear velocity and the shear velocity of the flow away from the bed to be 0.081 and 0.16 m/s, respectively, at the gaging station near National Canyon during the controlled flood. These values equal shear stresses of 6.6 and  $25.6 \text{ N/m}^2$ , respectively, and unit stream power values of 12.1 and  $46.8 \text{ W/m}^2$ , respectively. In contrast, Webb et al. (1999a) estimated that unit stream power ranged between 260 and  $2150 \text{ W/m}^2$  at 10 rapids during the low discharges of  $250 \text{ m}^3/\text{s}$  that occurred immediately before and after the flood. The magnitude of these values during the event would have been much greater. Except at rapids, these values are low in relation to measurements of other rivers during large floods (Costa and O'Conner 1995).

#### *Sediment transport during the 1996 controlled flood*

The total load of sand estimated to have been transported by the Colorado River during the seven days of the controlled flood was  $4.6 \times 10^5 \text{ m}^3$  and  $9.3 \times 10^5 \text{ m}^3$  past the Lower Marble Canyon and Grand Canyon gages, respectively (Schmidt 1999). These values are very small in relation to the pre-dam annual load of the Colorado River, which was primarily transported by longer duration floods of larger magnitude flows, but these values are large in relation to post-dam flows. The total sand load transported past the Lower Marble Canyon gage during the flood was approximately equal to 70% of the average annual sand load contributed by the Paria River, and the total sand load transported past the Grand Canyon gage was approximately equal to 60% of the average annual sand load contributed by the two largest tributaries, the Paria and Little Colorado Rivers (Schmidt 1999).

The concentration of suspended sediment transported by the test flood was within the historical range of suspended sand concentrations measured during unregulated snowmelt floods of the pre-dam river at discharges similar in magnitude (Topping et al. 2000). The highest concentration of suspended sand measured at three gaging stations during the flood was  $\sim 0.11\%$  and was measured at the Grand Canyon gage on the first day of the flood (Topping et al. 1999). The concentration of suspended sand transported past this site declined to 0.05% on the fifth day of the flood. The con-

centrations of suspended sand during the flood (Wiele et al. 1999) were much less than those of a 1993 Colorado River flood caused by a natural flood on the Little Colorado River, which was  $\sim 0.3\%$ , based on one measurement made by the U.S. Geological Survey (USGS) (Topping et al. 2000). These concentrations produced conditions of sediment depletion, which created coarsening of the bed grain-size during the controlled flood and pre-dam floods. The coarsening resulted in a distinctive "coarsening upward" grain-size distribution in mainstream flood deposits (Rubin et al. 1998, Topping et al. 1999, 2000).

#### *Landform changes*

*Reworking of debris fan deposits.*—Reworking of debris fans may cause the geometry of downstream eddies to change and thereby cause changes in the size and extent of backwaters formed by the sandbars that occur in those eddies. Webb et al. (1999a) showed that the flood was of sufficient magnitude to erode the streamside face of those debris fans that had been aggraded by debris flows that were  $<10$  yr old; little reworking occurred where debris flow deposits were older. Radio transmitters emplaced in boulders and recovery of marked boulders showed that these particles moved further downstream on the debris fans, into the deep pool immediately downstream from the rapid, and in one case, onto the cobble bar located downstream from the pool. Thus, the controlled flood not only reworked coarse debris delivered to the river from ephemeral tributaries, but also deposited cobbles and boulders in main channel pools and on cobble bars.

The greatest amount of reworking occurred at two debris fans where flows occurred less than two years before the controlled flood. Erosion of boulders from debris fans was by slab failure and by entrainment of individual particles from the bed (Pizzuto et al. 1999). Slab failures, wherein banks fail and boulders fall into the flow, provided initial motion to particles and allowed much larger particles to be moved than is predicted by traditional bed entrainment studies. Virtually all bank erosion at Lava Falls Rapid occurred during rising stage and during the first four hours of high steady discharge. This was probably the case elsewhere.

*Reworking of gravel bars.*—Although periphyton and aquatic macrophytes may have been scoured from gravel substrates in parts of Glen Canyon, significant bed material movement was not reported in this reach (Brock et al. 1999, Marzolf et al. 1999, McKinney et al. 1999). There were no specific studies of entrainment from gravel or cobble bars in Grand Canyon. However, Webb et al. (1999a) argued that the test flood was of insufficient magnitude to significantly rejuvenate cobble bars in Grand Canyon.

*Scour and fill of sand in fan-eddy complexes.*—Any flood has the potential to reconfigure fine-grained al-



luvial deposits and associated aquatic and riparian habitats, because the threshold of entrainment of fine-grained particles is much less than for coarser particles. This is especially the case with sandbars in large eddies, because bar configuration changes quickly when eddy flow patterns change. Scour and fill of the main channel bed may reconfigure main channel habitats, although the ecological importance of these bed configurations is unknown (Hoffnagle et al. 1999). There is a direct relationship between bed configuration and aquatic habitats in eddies, however, because of the relationship between the topography of reattachment bars and return-current channels. Scour and fill of previously vegetated areas has the potential to alter the distribution of riparian vegetation (Stevens 1989, Stevens et al. 1995).

There was a net transfer of sand from the channel bed to the banks and eddies. Hazel et al. (1999) measured net channel bed scour at 15 of 17 measurement sites upstream from the Grand Canyon gage, and Schmidt's (1999) sand budget for the controlled flood showed that sand was transferred from the bed to the banks. In some short reaches, however, bed topography was merely rearranged without net topographic change, such as near the Grand Canyon gage (Topping et al. 1999) and the National Canyon gage (Smith 1999).

Scour and fill was large in many eddy bars. Andrews et al. (1999) measured large day-to-day changes in the topography of eddy sandbars at five sites. There were areas of thick ( $>1$  m) deposition on the first day of the controlled flood at three sites between the Lower Marble Canyon and Grand Canyon gages. However, deposition rates at these sites declined during the next six days. Andrews et al. (1999) measured large erosion events from some eddies during the last few days of the flood; they described these events as mass failures from the eddies into the channels, caused by overloading of sand in eddies.

The longitudinal differences in main-stem sediment transport rates caused longitudinal differences in eddy deposition rates and in the average extent of erosion and deposition in eddies. These differences had the potential to cause variable patterns of ecological change, because the relative extent of erosion and deposition changed downstream. Schmidt (1999) showed that eddy deposition rates were lower at two sites upstream from the Lower Marble Canyon gage than at three sites further downstream where main-stem transport rates were twice as high as at the upstream site. Sondossi and Schmidt (1999) showed that the area of significant erosion in eddies within 15 km downstream from Lees Ferry exceeded the area of significant deposition, and that the area of significant deposition exceeded the area of significant erosion elsewhere. These field observations are supported by the modeling of Wiele et al. (1999), who developed a vertically averaged two-dimensional hydraulic model to demonstrate

that the size of reattachment bars depends directly on the concentration of suspended sand during each flood. Large reattachment bars are one necessary determinant of the size and persistence of backwater habitats. However, the extent of backwater habitats created by the flood also depended on the depth of excavation of the return-current channel, and changes in these two geomorphic features did not always change in a consistent way. Thus, changes in backwater habitats were measured directly.

New sand was primarily deposited within eddies and not as channel-margin deposits: between 49% and 80% of all new sand was deposited within eddies in the 31 km of channel mapped in detail by Schmidt et al. (1999b). Scour and fill occurred in similar places within each fan-eddy complex (Figs. 2 and 6). Most deposition occurred along the margins of the flood flow and near the zones of flow separation and reattachment; the thickness of new reattachment bars decreased upstream and downstream from this zone and most erosion occurred offshore in the deeper parts of the eddies (Hazel et al. 1999, Schmidt et al. 1999b).

Most of the nearshore deposition was not preceded by scour (Schmidt et al. 1999b). Thus, riparian vegetation on channel banks and channel margins was buried by as much as 1.5 m of sand (Parnell et al. 1999). However, riparian marsh vegetation growing on low elevation channel margins was eroded, either by scour or during failure of reattachment bars (Stevens et al. 2001 in this issue). Allochthonous organic matter consisted of vegetation produced by this process as well as organic material deposited in debris piles during earlier tributary floods. Some of this material was subsequently buried as mats of organic debris within the new flood deposits. Much of the woody phreatophytic vegetation that was merely buried survived the flood, resprouted, and recovered within the first growing season (Kearsley and Ayers 1999, Kearsley et al. 1999). However, redevelopment of fluvial marshes has been slow because of substrate grain size changes, steep bar face slopes, and reduced inundation frequency of aggraded surfaces (Stevens et al. 1995, 2001).

The sizes of fine sediment deposited by the flood coarsened with time. The percentage of silt and clay deposited with the sand was greater on the first day of the event than on following days, because silt and clay were flushed downstream during the first two days of the flood. (Rubin et al. 1998, Topping et al. 1999). Flood-deposited sediments would have had a higher silt and clay content if the flood had been of shorter duration. Thus, there is a potential to manipulate vegetation succession by controlling flood duration and the texture of deposits formed by those floods.

*Persistence of flood-formed sandbars.*—Readjustment of bars to moderately high flows following the controlled flood caused the area of exposed sandbars to decline rapidly. These summer flows ranged from

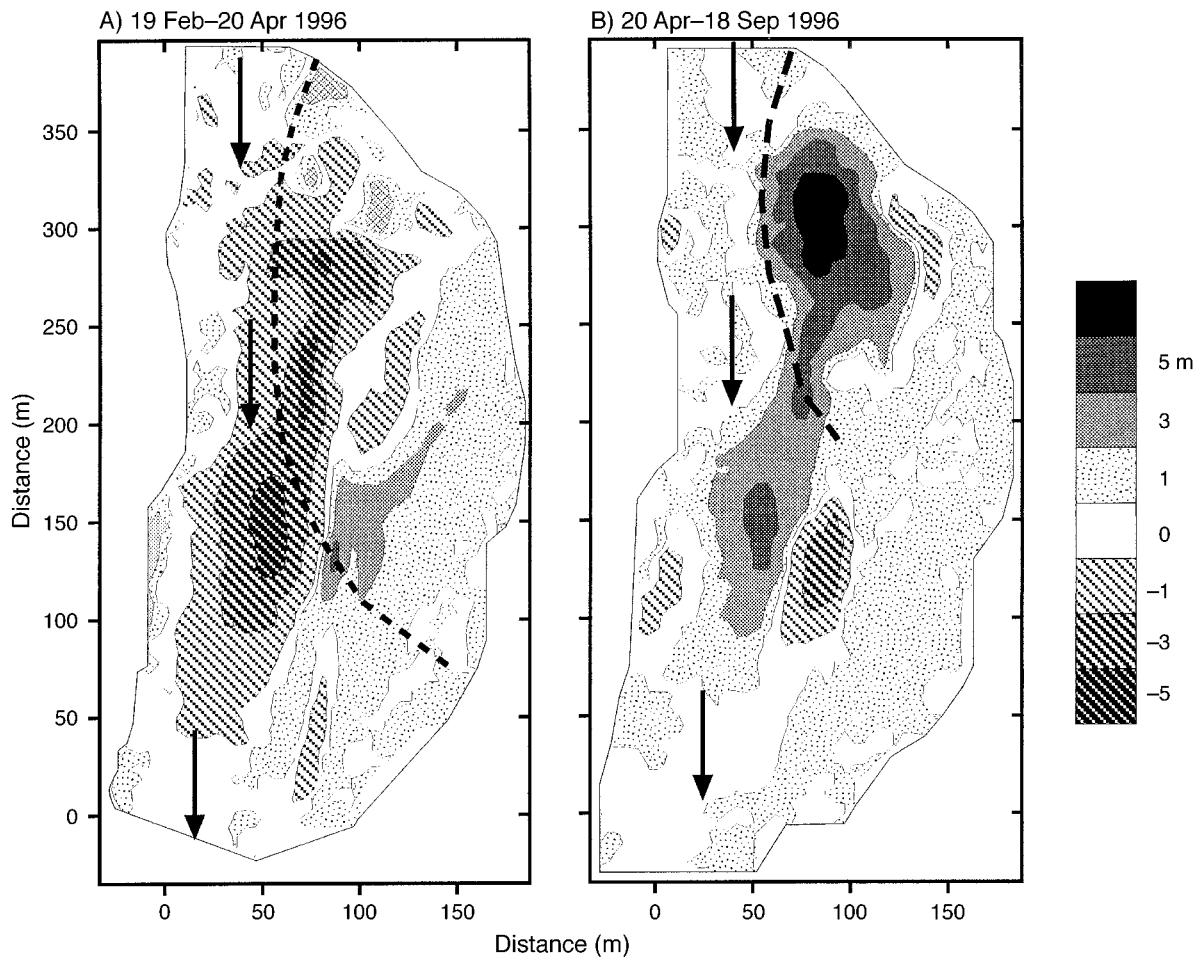


FIG. 6. Maps showing the sandbar at Rkm 85L (river kilometer 85, river left facing downstream; see Fig. 1 for location) showing zones of net erosion and deposition as a result of the controlled flood. The river flows from top to bottom; the eddy bar is on the right, and the river channel is on the left side. The dashed line represents the approximate position of the eddy fence dividing the main current (to the left) from the eddy recirculation zone (right). This pattern of erosion and deposition is typical of the response of many of the sandbars to the controlled flood, which were studied by Hazel et al. (1999). (A) Net erosion and deposition immediately following the controlled flood. (B) Subsequent net erosion and depositional patterns for the following five-month period.

421 to 523  $\text{m}^3/\text{s}$  (Fig. 5). The general trend occurring throughout the summer was for sand deposited above the elevation of the maximum stage reached by post-flood dam releases to be eroded and transported into the subaqueous parts of the eddy and main channel (Fig. 7). For the five-month period following the flood, the high elevation parts of the bars lost 9% of their volumes each month (Hazel et al. 1999). This erosion rate decreased to between 2% and 4% per month for the next five-month period.

**Terrestrial habitat rejuvenation.**—The controlled flood caused physical and chemical changes which affected the terrestrial system. Burial of autochthonous and allochthonous vegetation by test flood deposits resulted in significantly increased rates of organic matter mineralization and release of dissolved, inorganic P and N and organic C into the root zones of the bars

(Parnell et al. 1999). This pulse of nutrients, in unknown combination with increased water availability produced by extended periods of relatively high river stage following the flood, may have had a positive impact on terrestrial productivity (Stevens 1989, Stevens et al. 2001).

**Backwater habitat rejuvenation.**—We analyzed backwater distribution from Glen Canyon Dam to Lake Mead using aerial videography collected during steady research flows of 227  $\text{m}^3/\text{s}$  on 24 March, 7 April, and 2 September 1996, and on 1 September 1997, considerably extending the work of Brouder et al. (1999). We used Map Image Processing Software (MIPS; MicroImages 1995) to view and locate each backwater, assign it a specific site name, digitize and determine its area, and describe its geomorphic setting. The area of each backwater was measured three times. Ground

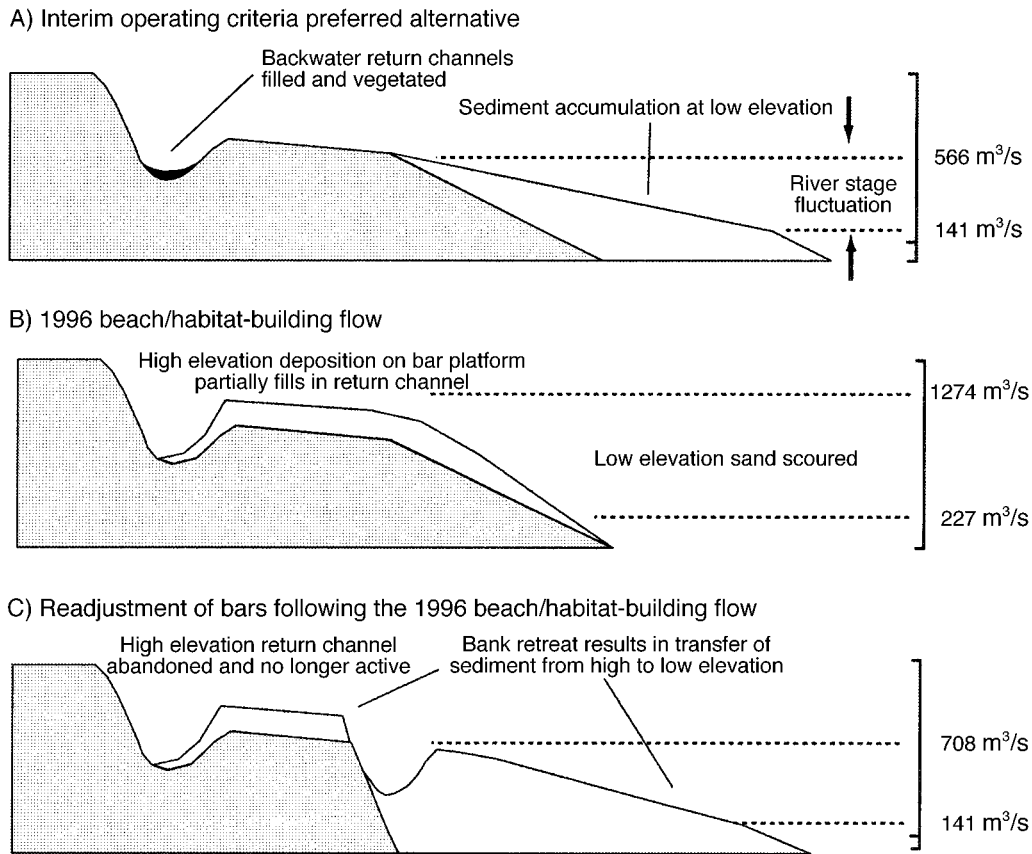


FIG. 7. Diagrams showing typical changes in bar topography and changes in backwater channels throughout Grand Canyon caused by the 1996 controlled flood. (A) During average flow conditions before the flood, river water did not inundate the bar or the return channel. The bar was eroding, and the return channel was infilling with vegetation. (B) Immediately after the flood, the bar platform had been aggraded, the return channel partially filled in, and the channel area offshore eroded and deepened. (C) In the 10 mo following the test flood, erosion from the high-elevation parts of the bar produced a sediment source for deposition in the eddy and main channel. A new return channel of lower elevation was established by bank retreat as eddy currents produced by the high steady flows after the test flow created and eroded the cut bank of the bar.

truth for the aerial photo imagery was established using up to three ground control points around each of 30 backwaters. We regressed remotely measured distances among these control points to MIPS measurements at these sites for each run. We adjusted MIPS area measurements using the mean regression equation for that run.

The abundance and area of backwaters detectable at a discharge of 226 m<sup>3</sup>/s increased after the controlled flood (Fig. 8), consistent with the observations of Brouder et al. (1999) on a subset of backwaters. The total number of backwaters increased from 109 on 24 March to 164 on 6 April 1996, a 1.5-fold increase (Friedman's  $t = 4.083$ ,  $P = 0.043$ ,  $df = 1$ ). Total backwater area also increased as a result of the test flood, from 6.09 ha to 13.95 ha, a 2.29-fold gain (Friedman's  $t = 4.083$ ,  $P = 0.043$ ,  $df = 1$ ). However, backwater abundance only increased in Glen Canyon and Marble Canyon, and not in reaches further downstream, including places that are of most concern for native fish

(Fig. 8). Thus, there was spatial variability in the response of backwaters to the flood. The number of backwaters increased in only a few reaches and not in the reaches most critical to the life history needs of the humpback chub.

The resumption of normal dam operations decreased the available area of backwaters, but not their abundance. The total number of backwaters increased during 1997, even though this was a period when there was widespread erosion of flood-deposited eddy bars. The total number of backwaters was 175 on 31 August 1997 (Fig. 8). However, backwater area dramatically decreased to 2.36 ha (Friedman's  $t = 8.333$ ,  $P = 0.004$ ,  $df = 1$ ) during the first six months after the flood, and remained essentially unchanged through 1997. The loss of backwaters during the first six months constituted a 5.9-fold loss, and a 2.6-fold decrease in relation to the pre-flood backwater area (Fig. 8). These changes were probably related to the transfer of sand from high to low elevation, and the establishment of new flow pat-

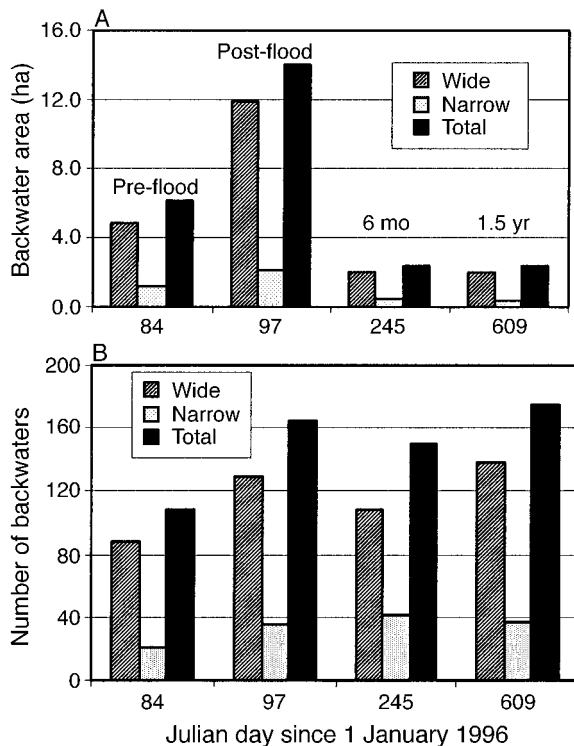


FIG. 8. (A) Backwater area and (B) number of backwaters before and after the flood in the Colorado River corridor between Glen Canyon Dam and Separation Canyon (river kilometer 386), on 24 March, 6 April, and 1 September 1996, and 31 August 1997, measured using Map Image Processing Software (MIPS) from aerial videographic images.

terns in eddies caused shifts in the location and shape of the primary eddy return-current channel. New eddy flow geometries developed on the channel side of the high elevation bars, creating new, lower elevation return-current channels which were isolated from the main stem only at very low flows (Fig. 7).

#### DISCUSSION AND CONCLUSIONS

The controlled flood was a small physical disturbance in relation to pre-dam river conditions in terms of its magnitude, total volume of water, duration, and in relation to the magnitude of the baseflows immediately before and after the flood. The flood was also unusual in its timing and occurred much earlier in the year than any previously measured high flow of this magnitude. Thus, this flood did not have the potential to rework physical habitats in a similar manner to pre-dam floods.

In terms of post-dam river conditions, the controlled flood was a much larger hydrological event. The flood was one of seven high flow events that have occurred since completion of Glen Canyon Dam in 1963. Post-dam floods of this magnitude previously occurred in 1965, 1980, and annually between 1983 and 1986. The flood had a recurrence of 5.1 yr, and the flood occurred

after a 10-yr period when the flow did not exceed power-plant capacity. The flood inundated high elevation fine-grained alluvial deposits that had not been under water since 1986, and most of these deposits were extensively overgrown by riparian vegetation (Stevens 1989, Stevens et al. 1995). The dense riparian vegetation undoubtedly made erosion of these areas more difficult.

The sediment supply available for transport by the controlled flood was much less than pre-dam floods. The largest geomorphic effect of this flood was to redistribute fine sediment from low elevation to higher depositional sites along the channel margin; at the same time, some fine sediment was exported to Lake Mead. Fine sediment redistributed to high elevation represented one type of "improvement" to the ecosystem caused by the flood; fine sediment delivered to Lake Mead represented one type of "loss." Schmidt (1999) estimated that as much fine sediment was exported from Marble Canyon as was deposited along its banks and in eddies, and he estimated that the ratio of export to deposition increased further downstream. Upstream from the Little Colorado River (LCR), most of the sand in transport was eroded from low elevation parts of eddies; downstream from the LCR, most of the sand was derived from the bed.

The flood's water and sediment flux left their mark on the low elevation fine sediment components of the physical template of the riverine ecosystem, because fine sediment deposits are easily entrained at the velocities typical of the main current and in eddies at flood stage. In contrast, reworking of coarse-grained debris flow deposits was confined to a small subset of debris fans that had been aggraded in the decade prior to the flood. As with any river, the distribution of velocity exhibits a strong gradient from highest near the center of the main current and lowest at the bed and banks. In the fan-eddy complexes of Grand Canyon, very low velocities also occurred near the zones of flow separation and reattachment that occur at the upstream and downstream ends of eddies.

These spatial patterns of velocity change resulted in a spatially variable arrangement of areas of deposition and erosion caused by the flood. Fluvial marshes, which typically occur near the stage of the post-dam baseflows, were extensively eroded. Elsewhere, low elevation sandbars that create backwaters at low river stage were also extensively eroded. In contrast, near-shore deposition was widespread, because the net direction of sediment transport was from the channel center towards its banks and nearshore velocities were low. Thus, there was little erosion near the water's edge of the 1996 controlled flood, and riparian shrubs were buried and not scoured. Changes in flow patterns also caused the re-excitation of return-current channels. Erosion of these channels, along with deposition of the higher elevation parts of reattachment bars led to a net



increase in backwater habitat that persisted for at least six months after the flood.

Recovery follows disturbance in any fluvial system (Wolman and Gerson 1978), and the flood-induced changes only lasted a few years. Some flood-induced changes disappeared very quickly: bar faces were rapidly reworked, backwater area quickly decreased, and some riparian plant species quickly regrew on aggraded bars (Kearsley and Ayers 1999). Elsewhere, flood-induced changes had longer persistence: flood-deposited high elevation sand still is abundant along the river, but is now approaching its pre-flood sizes (Kaplinski et al. 1999). The number of backwaters in the river corridor was still larger in 1997 than the number immediately before the flood, but the areas of those backwaters had decreased greatly. There was enhanced soil nutrient availability for at least two years.

Other changes are of long-term consequence: the coarsened surface texture of the substrate has the potential to affect riparian vegetation successional dynamics. The 9- to 17-yr periods without floods allowed the proliferation of riparian vegetation (Turner and Karpiscak 1980, Johnson 1991, Stevens et al. 1995, Webb 1996). The creation of higher bars with a coarser texture than that which existed prior to the flood reduces potential recolonization by wetland and some riparian plant species (Stevens 1989, Stevens et al. 1995, 2001).

Deposition of new sediment occurred directly over pre-existing vegetation on reattachment bars. This burial initiated a unique pulse of nutrient availability in backwaters and bar soils that lasted for up to two years, and may have stimulated bar vegetation regrowth (Parnell et al. 1999). Rapid regrowth of buried clonal marsh plants (i.e., *Equisetum* spp., *Phragmites australis*, and *Scirpus pungens*) on steep bar faces may have reduced erosion rates during the two years following the test flood. Although the role of shrubs in preventing scour and fill along the channel banks was not studied, the low velocities of these areas makes it unlikely that scour would have been large, even in the absence of vegetation.

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